Cosmic-ray ensembles simulations

O. Sushchov, P. Homola

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Outline

1. Cosmic-ray ensembles (CRE)
2. Motivation
3. Photons and cosmic-ray ensembles
4. Generalizing research strategy
5. Scenarios examples
6. Simulations status

Motivation: testing astrophysical scenarios

Bottom → Up: Astrophysical scenarios

acceleration of nuclei (e.g. by shock waves)

+ "conventional interactions", e.g. with CMBR

- sufficiently efficient astrophysical objects difficult to find
- small fractions of photons and neutrinos – mainly nuclei expected

Top → Down: Exotic scenarios (particle physics)

Decay or annihilation the early Universe relics

→ hypothetic supermassive particles of energies $\sim 10^{23}$ eV

→ decay to quarks and leptons → hadronization (mainly pions)

large fraction of photons and neutrinos in UHECR flux

Experimental evidence about UHE photons

γ_{UHE} —no interactions / screening→ **Earth**

NOT OBSERVED

γ_{UHE} —unexpected interactions, screening, ...→ **ELECTROMAGNETIC CASCADES (Cosmic-Ray Ensembles)** → **Earth**

NOT TRIED SO FAR...

↓

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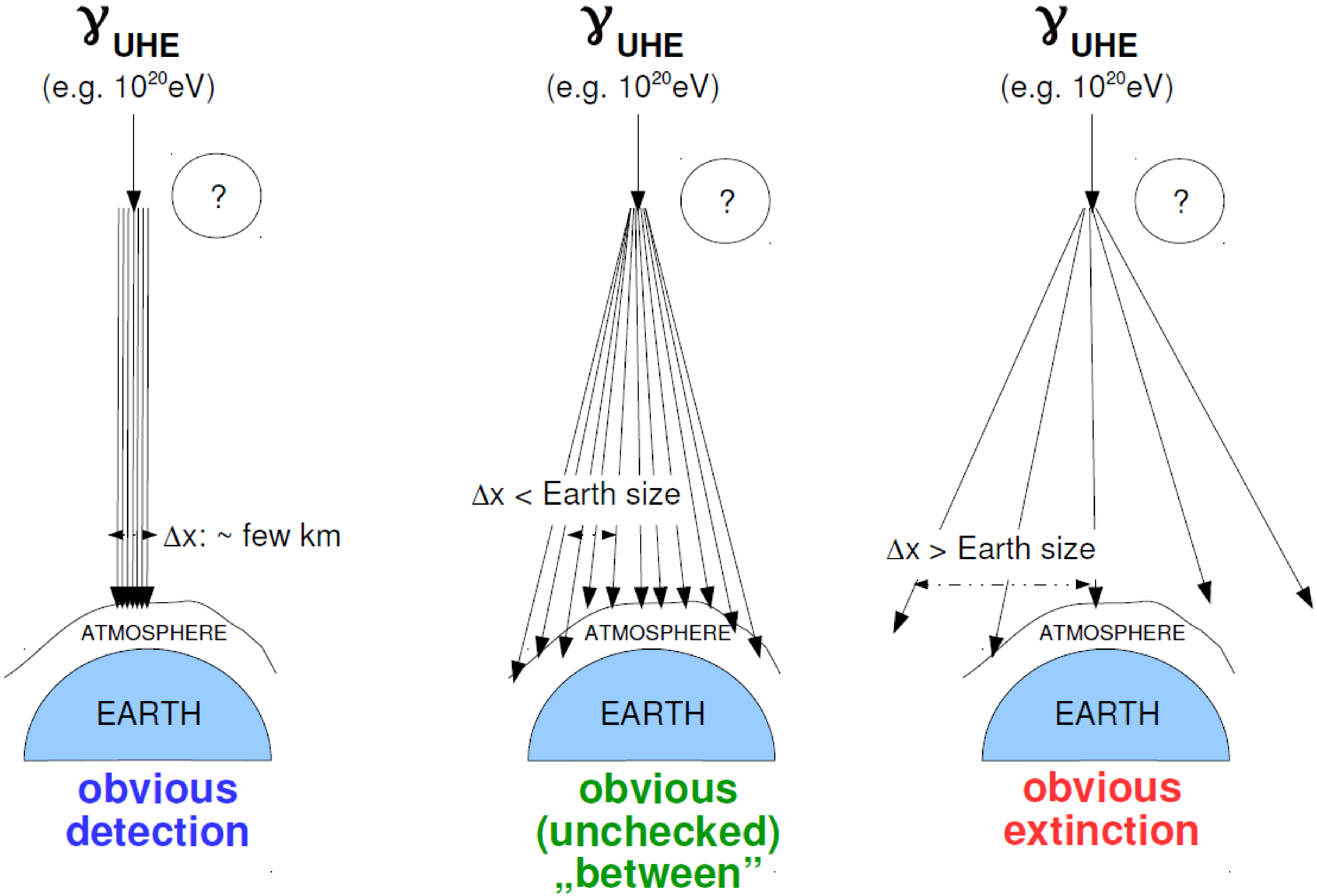
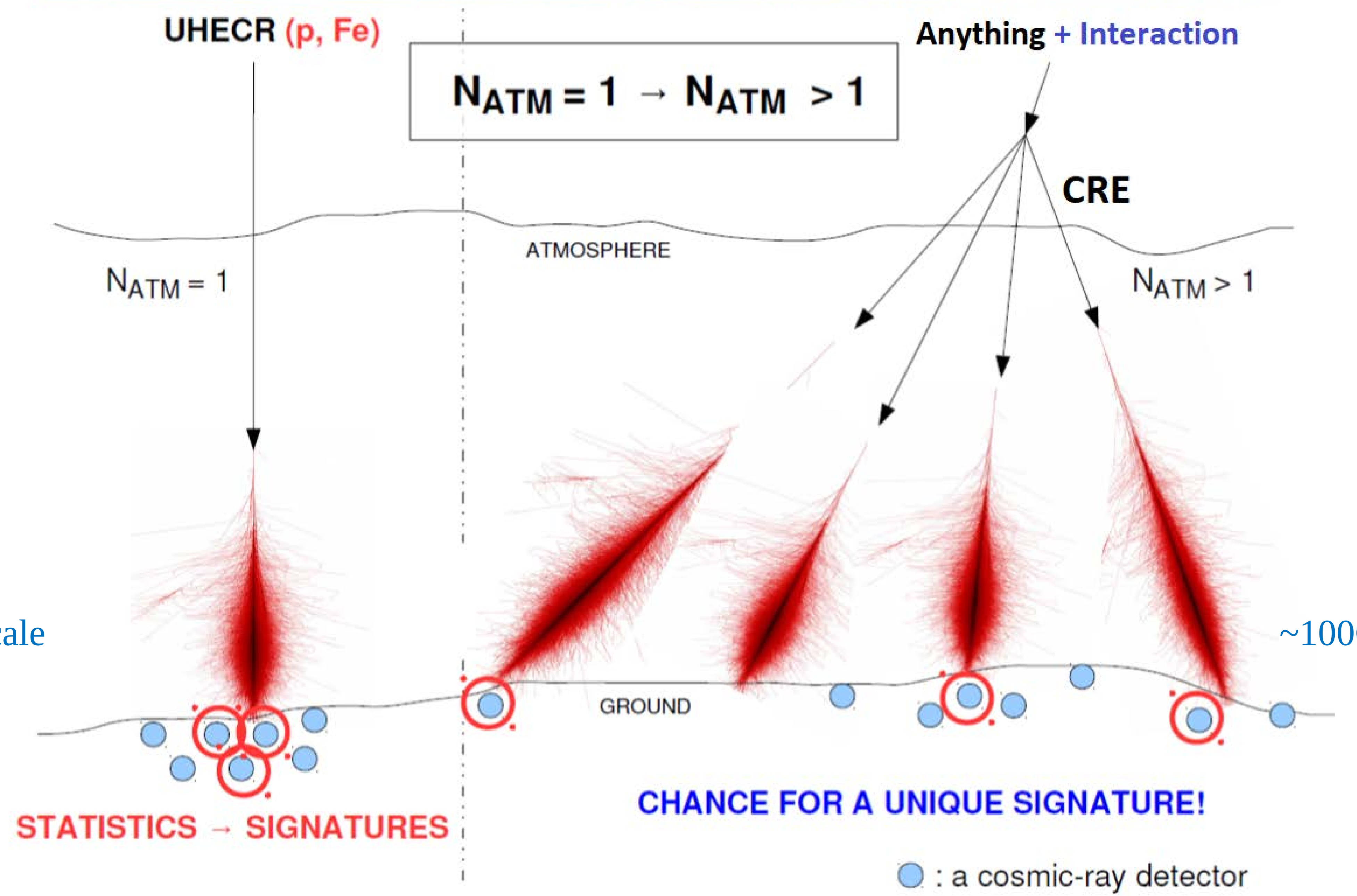
Cosmic ray ensembles on Earth: untouched ground



Generalized detection of cosmic rays



~10 km scale

~1000 km scale

Cosmic-Ray Ensembles: road map

Theoretical scenarios (ongoing)
non-exotic / exotic ✓

↓

CRE standalone simulations → particle distributions at the top of the atmosphere (ongoing) ✓

↓

Air shower simulations (ongoing) ✓

↓

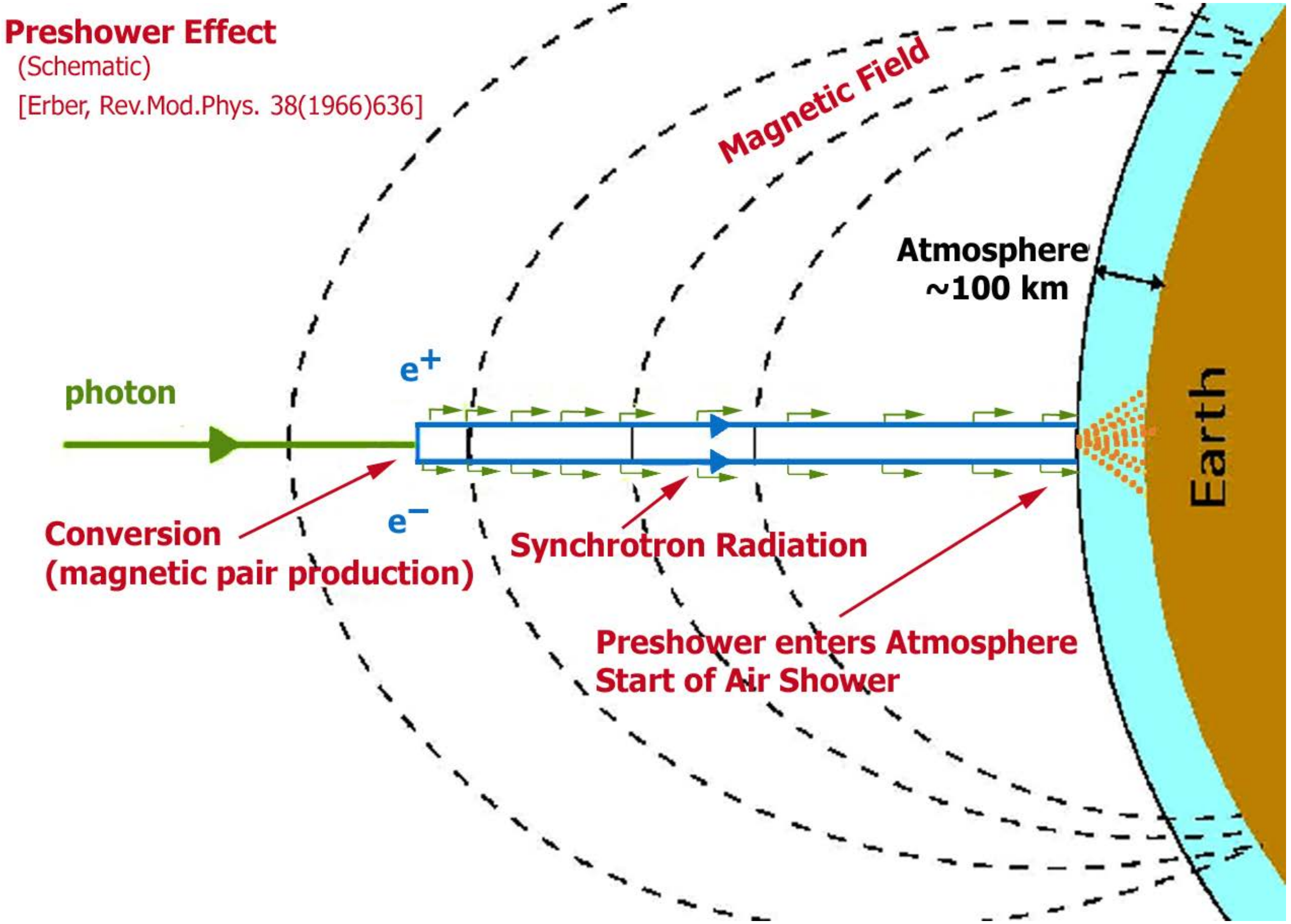
Detector response (ongoing) ✓

↓

observation / upper limits

Example non-exotic scenario: Sun cosmic-ray ensembles

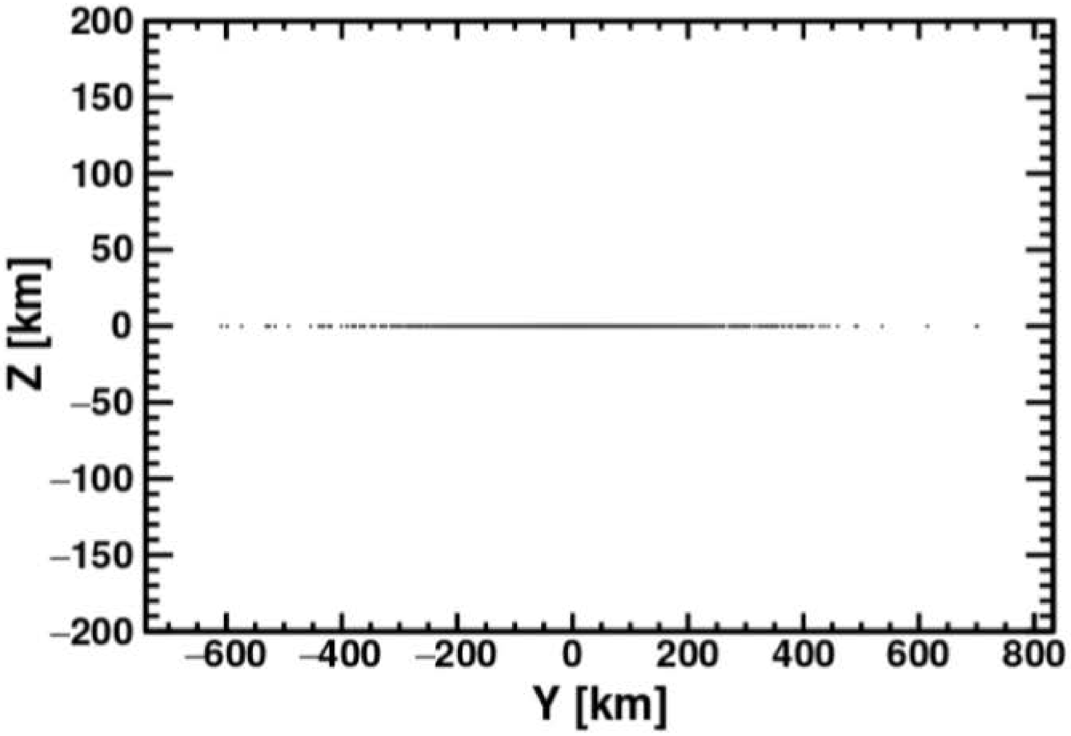
Preshower (important for E > 10^{19} eV):
→ contains typically 100 particles
(created at around 1000 km a.s.l.)



→ dependence on E and $B_{\perp}$ (to be seen in data?)

Distribution of photons at the top of atmosphere

Example 1: Magnetic moment of the Sun is along its rotation axis. Primary photon heading towards Earth travels in the Sun's **equatorial** plane.

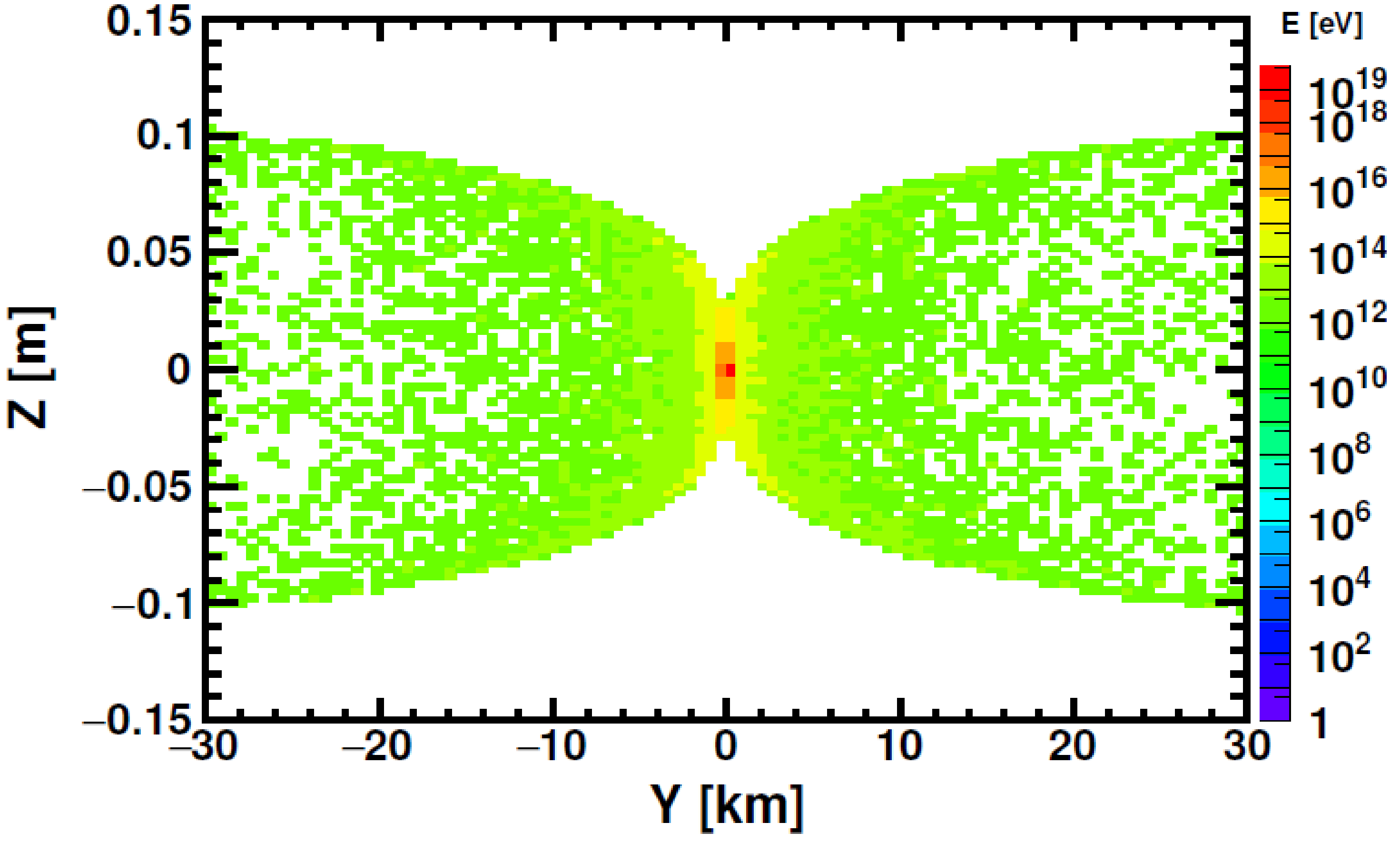


- **Large number of photons** ($\sim$ 50000) at the top of the Earth's atmosphere.
- Photons distributed over a **very large distance** along a **line**.

Distribution of photons (with $E > 10^{13}$ eV) at the top of the Earth's atmosphere. Energy of the primary photon = 100 EeV, impact parameter = 2.5 $R_\odot$.

Slide by N. Dhital, INP PAS

Distribution of photons at the top of atmosphere



Zoomed-in, previous plot

- smaller deflection of photons

↓

- higher energy

↓

- photons more confined in the "core region"

Slide by N. Dhital, INP PAS

Example exotic scenario: Lorentz invariance violation

- κ endows the vacuum with an effective index of refraction, leading to a **modification of the photon dispersion relation**

$$\omega(q) = \frac{1}{n_{\text{eff}}}\, q = \sqrt{\frac{1-\kappa}{1+\kappa}}\, q$$

- This modification allows for processes which are **kinematically forbidden** in the conventional Lorentz-invariant theory
  - $\kappa > 0$: **vacuum Cherenkov radiation** possible above a threshold $E_{\text{thr}}(\kappa)$

    $$f \to f + \tilde{\gamma}$$

    efficient energy loss mechanism for charged particles, current constraints ($\kappa < 6 \times 10^{-20}$ at 98 % C.L.) derived from **observations of UHECRs** [Klinkhamer & Risse 2008] [Klinkhamer & Schreck 2008]
  - $\kappa < 0$: **photon becomes unstable** above a threshold $\omega_{\text{thr}}(\kappa)$

    $$\tilde{\gamma} \to e^{+} + e^{-}$$

    decay length is very small, current constraints ($\kappa > -9 \times 10^{-16}$ at 98 % C.L.) derived from **gamma-ray astronomy** [Klinkhamer & Schreck 2008]

ALL UHE photons initiate CRE!!!

F.R. Klinkhamer, M. Niechciol, M. Risse. arXiv:1710.02507

Simulations' methodology

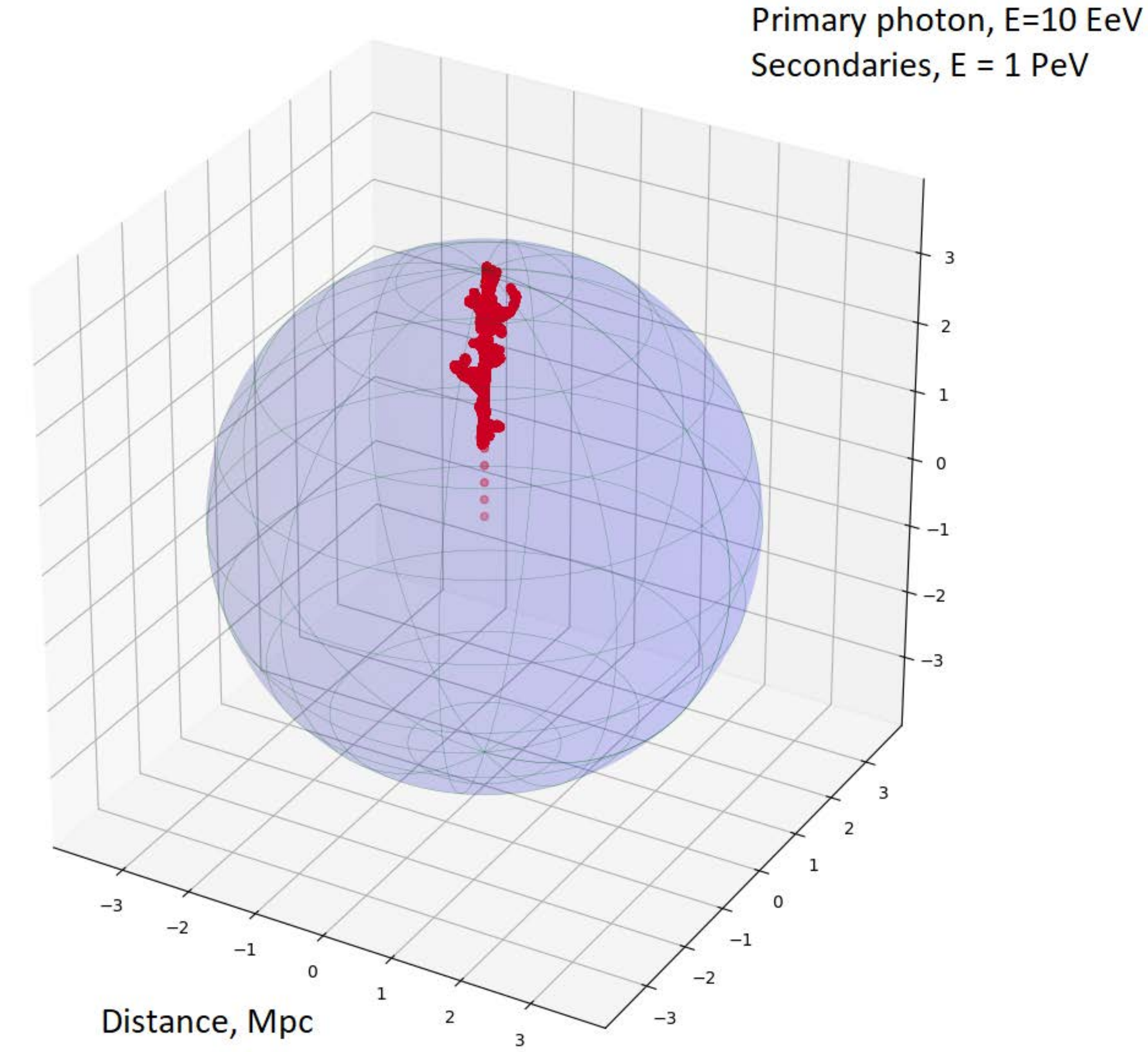
CRPropa3

[https://github.com/CRPropa/CRPropa3,

https://arxiv.org/abs/1603.07142]

3D simulations of a photon primary propagation

1. Simplest case – { GMF (JF12) + } EGMF
2. Accounting for synchrotron radiation (computational issues)
3. Specific cases (e.g. neuron star environment)
4. …



CREDO: mission organized for cosmic ray ensembles

Cosmic-**R**ay **E**xtremely
Distributed **O**bservatory

Central database/interface: access to everything for everybody